Active Matrix Display Layout Optimization for Sub-pixel Image Rendering

Candice Hellen Brown Elliott
ClairVoyante Laboratories, Inc., Sebastopol, Calıfornia, USA
URL: http://www.pentile.com Email: candicc@pentile.com

Subpixel rendering on conventional stripe subpixel displays has been demonstrated to double the addressability in the horizontal axis of the display Graphics rendering to obtain color subpixel pitch addressability is enhanced by optimization of the subpixel positioning and addressing circuit with respect to human vision, resulting in the PenTile Matrix™ subpixel architecture to double the addressability and increase the MTF in both horizontal and vertical axises The pixel is divided into five subpixels. two red, two green, and one blue The data driver for the blue subpixel is shared with a neighboring pixel's blue subpixel, reducing the number of data drivers on a display, offsetting the increase of gate drivers. Thus, a display using the optimized PenTile Matrix™ architecture and subpixel rendering delivers quad addressability and improved image quality for nearly the same manufacturing cost

Introduction

This paper describes ongoing development of a Thin Film Transistor Active Matrix Liquid Crystal Display (TFT AMLCD) layout optimized for subpixel rendering, the *PenTile Matrix*™ subpixel architecture This work commenced in 1993 Recent developments by other firms to commercialize subpixel rendering have focused on software algorithms for conventional, non-optimized, color panels. Subpixel rendering has been demonstrated useful for improving the image quality of Western fonts and full color graphics on conventional, non-optimized, RGB stripe, triad, and bayer pattern LCD panels using displaced box filter decimation [1][6] and tent filters [4][6] as early as the mid-1980s. This present work focuses on simultaneously optimizing both the subpixel layout and the subpixel rendering algorithm To optimize the subpixel layout requires an understanding of human vision [3].

Interest in electronic publishing, eBooks, has prompted two leading software firms to announce development and product plans for using subpixel rendering, or "color anti-aliasing" to improve font quality on LCDs [5][7][8]. Similarly, major publishing houses are investing in conversion of their titles to eBook formats [11]. Since portability is perceived as important for successful eBook products, the increasing demands on laptop computer displays, and because of the recent trend of replacing desktop CRTs with LCD monitors, the need for improved image quality on LCDs, especially of text fonts, is driving software developments. This same need is driving the present development of a subpixel arrangement optimized for subpixel rendering.

With subpixel rendering set to become an established technique, now is the best time to optimize and standardize the subpixel layout to achieve greater benefit from subpixel rendering. The present work, introducing the *PenTile Matrix*™ subpixel arrangement, is offered as the future standard for flat panel displays

Human Vision

Three color receptor nerve cell types called cones produce full color perception in the eye. The three types are sensitive to different wavelengths of light: long, medium, and short ("red," "green," and "blue" respectively). There are slightly more red receptors in the eye than green. There are also very few blue receptors compared to red and green [13], the ratio being 1 to 14 respectively. While in the fovea, the area that has the highest resolution capability, the number of blue receptors drops to less than one in twenty.

The human vision system processes the information detected by the eye in several perceptual channels· luminance, chrominance, and motion. The luminance channel takes the input from the red and green cones combined, ignoring the blue The chroma channel is further divided into two sub-channels, the red-green opposition channel, and the yellow-blue opposition channel. The red and green colors combine to form the yellow that is opposed to the blue color [12].

The luminance channel resolution limit is approximately 50 cycles per degree in the horizontal axis, while the yellow-blue chroma sub-channel resolution limit is 4 cycles per degree [13]. Since saturated blue does not contribute to high-resolution images in human vision, reducing the number of blue pixels does not lower the image quality [2][9][10] Conversely, increasing the number of blue subpixels does not improve image quality [3].

In subpixel rendering the red and green subpixels each contribute to high-resolution images, but the blue subpixel does not. Since the blue subpixel does not significantly contribute to the luminance channel, adjustments in blue brightness do not 'pull' the optical 'center of gravity' of a group of subpixels as strongly as either red or green. To put it simplistically; Blue subpixels don't count.

Human vision does not have the same resolving power in each direction The horizontal axis is best, but almost the same as the vertical, however, the diagonal directions have significantly lower resolving power than either the horizontal or vertical. This is why half-toning patterns are set such that the lowest dot pitch is in the diagonal directions. One common half-toning pattern is a simple black and white checkerboard with rows and columns aligned with the horizontal and vertical axises.

Subpixel Rendering on Color Patterned Displays

Subpixel rendering, in its most simplistic implementation, operates by using the subpixels as approximately equal brightness pixels perceived by the luminance channel. This allows the subpixels to serve as sampled image reconstruction points as opposed to using the combined subpixels as part of a 'true' pixel. By using subpixel rendering one increases the spatial sampling, reducing the phase error.

If color of the image were to be ignored then each subpixel may serve as a though it were a monochrome pixel, each equal. However, as color is nearly always important (and why else would one use a color display?) then color balance of a given image is important at each location. Thus, the subpixel rendering algorithm must maintain color balance by ensuring that high spatial frequency information in the luminance component of the image to be rendered does not alias with the color subpixels to introduce color errors. If the image is monochrome, then a simple five subpixel wide horizontal tent filter applied after subpixel rendering may suffice [4]. However, such filtering will significantly reduce the saturation of full color images. Another approach is similar to a common anti-aliasing technique, applying displaced decimation filters to each separate color component of a higher resolution virtual image. This ensures that the luminance information does not alias within each color channel [1][6].

It is important that the chroma values be linearly additive, that is to say, that the pixel rendering must be done before gamma correction. The outputs of the algorithm may feed into the gamma correction tables. If gamma correction is performed before subpixel rendering, or no gamma correction is performed, unexpected chroma errors are likely to occur.

For subpixel rendering to work, it is important that the algorithm know the location of each color subpixel. It must be performed after, or be part of, any scaling of the image that occurs. This is especially of concern for the growing LCD monitor market, as many of these monitors perform scaling as part of "Multi-Sync" support. Should the software in the computer be assuming a different display resolution than the actual display, the monitor's scaling of the image to the real display will distort the subpixel rendering information, leading to unexpected chroma and phase errors. The image quality will be seriously compromised. The best location for subpixel rendering in such cases is within the monitor itself, in the display controller.

Since the display controller cannot add information, only map it, the computer must deliver conventional, non-subpixel rendered images to the monitor, to be subpixel rendered by the display controller in the monitor, that is higher than the nominal resolution of the display.

If the arrangement of the subpixels were optimal for subpixel rendering, subpixel rendering would provide an increase in both spatial addressability, to lower phase error, and Modulation Transfer Function (MTF), high spatial frequency resolution, in both axises.

Subpixel Rendering on RGB Stripes

Examining the conventional RGB stripe display, one notes that subpixel rendering will only be applicable in the horizontal axis. Since in a display with ideal color filters, only the red and green pixels are useful in subpixel rendering, the effective increase in addressability would be two fold, in the horizontal axis. However, the blue color filter is not an ideal filter. It is slightly de-saturated. To the extent that it allows medium and long wavelengths of light (green and red respectfully), the blue filter does contribute to the human vision luminance channel and thus to subpixel rendering. Thus the effective addressability has been described as being increased between 200-300% [5]. For most wide color gamut blue filters, the subpixel addressability may be assumed to be only marginally better than two times the pixel pitch in the horizontal axis.

Since vertical black & white lines must have the two dominant subpixels, red and green per each black or white line, in each row, the Modulation Transfer Function (MTF) is not enhanced by subpixel rendering. Thus, the conventional RGB stripe subpixel arrangement is not optimal for subpixel rendering.

Optimizing the Subpixel Arrangement

The first tool towards optimization is to pull the blue subpixel "out of the way", by temporarily ignoring it, since it does not add as much to subpixel rendering.

Now we see only red and green pixels. What is the best arrangement of two colors? The goal is to increase the spatial addressability in the vertical axis and MTF in the both vertical and horizontal axises. The red and green subpixels are divided in half in the vertical axis to increase addressability. A further hint comes from the problem of improving the MTF of the display. The fact that the conventional stripes limited the MTF in the horizontal axis tells us that stripes of a single color are non-optimal. If in a single vertical stripe, both colors were available, then a single vertical stripe would provide full color capability. Likewise if in a single horizontal stripe, both colors were available, then a single horizontal stripe would provide full color capability. The optimal arrangement has both red and green subpixels in each vertical and horizontal stripe. Thus an alternating 'checkerboard' of red and green subpixels allows the MTF to increase with subpixel rendering.

The red and green checkerboard, like the common newspaper half-toning pattern, has the highest resolution in the vertical and horizontal axises. The diagonal resolution is the square root of two lower, matching the human visual system's resolving power.

Turning back to the blue subpixel, two points need to be considered. The pixel array should be largely rotationally symmetrical and have equal red, green, and blue area. This is achieved by placing a large blue subpixel in the center of the pixel. The result is the *PenTile Matrix*™ arrangement of subpixels in Fig. 1.

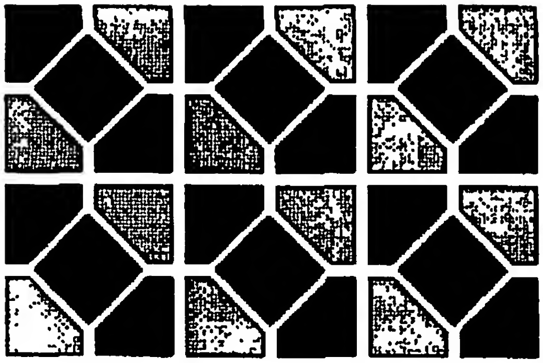

Figure 1. PenTile Matrix™ arrangement of subpixels

Subpixel Rendering on the PenTile Matrix™

To reach the highest image quality the *PenTile Matrix*™ display is capable requires subpixel rendering. ClairVoyante™ subpixel rendering algorithm defines a logical pixel at each red and green subpixel location. The blue does not have a logical pixel associated with its position; rather it is treated as a super-pixel, shared by the surrounding four logical pixels. Since there are four logical pixels assigned to each *PenTile Matrix*™ pixel, the input data to the subpixel rendering system is a quad resolution image. Each logical pixel assigns a weighted mapping of the conventional software logical pixel's three color values, RGB, with the color subpixels on the display.

To illustrate, shown in Fig. 2 is a single logical pixel showing a single bright white dot, software pixel, centered on the green subpixel. The green subpixel is set to 50%; the four surrounding red subpixels are set to 12.5%, while the blue is set to 25%. Thus, the energy of the original white dot is spread over six subpixels in a gaussian spot, much like that displayed by CRTs. Note that the blue is treated separately from the red and green. The red and green combined add up to 100%. While the blue is simply 25%, one fourth, of the total energy available to it, since it is shared with four logical pixels and carries only chroma information.

When logical pixels are displayed next to each other, the values of the overlapping logical subpixels add. Thus, if all of a given area of an image to be rendered is white, the values for each of the subpixels add up to 100%. Calculating the value of each subpixel at first appears complicated, but in fact the reverse is true. The value of any given subpixel is simply half of the input value of the original software pixel of that color at that location with the rest of the energy coming from the surrounding four software pixels.

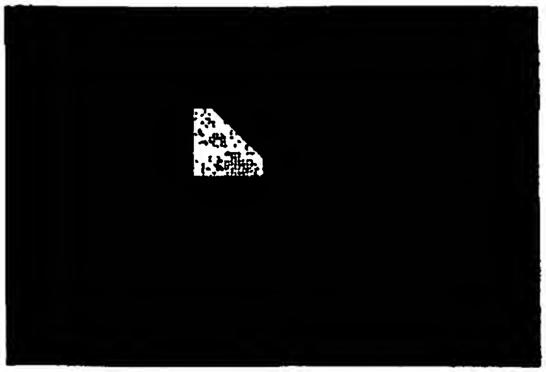

Figure 2. White dot rendered at green subpixel location: each red = 12.5%, green = 50%, blue = 25%.

The *PenTile Matrix*™ subpixel rendering algorithm is thus a displaced two dimensional tent filter for the red and green subpixels and a centered box filter for the blue subpixels. The algorithm directly maps a quad resolution image to the display, with each software pixel's red, green, and blue values being remapped at the subpixel level onto the display. The algorithm may be performed in software or hardware. The algorithm uses only bit shift division and addition. In hardware, an estimated five thousand gates is all that is required, easily incorporated in the display timing controller. Thus, a *PenTile Matrix*™ SVGA display would be directly driven by UXGA images, with no loss of image quality.

Optimizing the AMLCD Layout

Shown in Fig. 3 is a rough layout of the *PenTile Matrix*™ architecture for AMLCD. Not shown in Fig. 3, for clarity, are the storage capacitors for the subpixels, which are shown in detail in Fig. 4. The two column data lines of the blue pixels are tied together and driven by a single driver. The blue pixels in a row are selected by alternating row gate lines. The red and green columns and rows are selected in the conventional manner by the data and gate lines as shown.

By placing drivelines in pairs, space is saved, as two lines on the same layer may be placed closer together than interlayer design rules would allow. Thus the aperture ratio is improved.

Grouping the TFT switches of the red and green subpixels together forms a dark spot on the display at the same pitch but 180° out of phase with the blue pixel, which is also perceived as a dark spot in the human vision luminance channel. By adding these dark dots the spatial frequency of the combined blue subpixel and switches is pushed higher, and thus less noticeable .

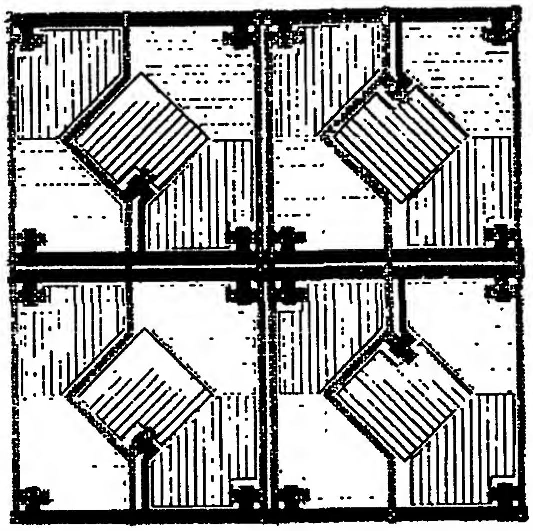

Figure 3. PenTile Matrix™ TFT AMLCD Layout

By alternating the gate line that is used to address the blue subpixels in a given row, the data line for neighboring blue subpixels may be tied together to share a single data driver. This reduces the number of data drivers by 16.7%, offsetting the increased number of gate drivers. Depending on aspect ratio of the panel, the total number of drivers may increase, remain constant, or actually decrease, as it would in the case of 16:9 HDTV type aspect ratio panels. Even should the total number of drivers increase, the total cost is still likely to be lower, as the decrease is of expensive data drivers and the increase is of less expense gate drivers.

The decrease in the number of data drivers allows assembly of higher nominal resolution displays, as one of the limiting factors is the contact pitch. With 16.7% less drivers per pixel, present data driver packaging will allow a corresponding increase in pixels per panel of the same size, if desired.

The subpixel storage capacitors are constructed using "capacitor on gate line" technology. The capacitors for the red and green subpixels are constructed on top of the nearest gate line not associated with that row. The ITO is used to crossover the associated gate driver to connect to a capacitor electrode on the data line metal layer, above the non-associated gate line. The blue subpixel capacitor is constructed similarly, but uses the gap between the red and green subpixels. At the top and bottom of the array are dedicated capacitor lines.

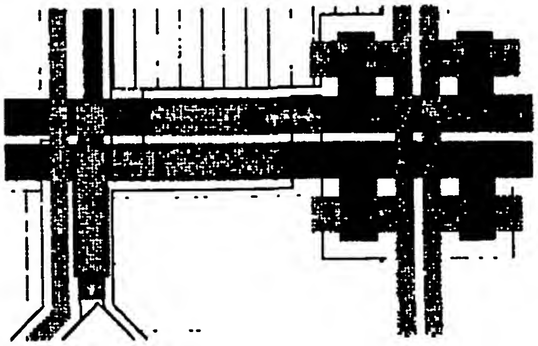

Figure 4. Detail of Storage Capacitors

In the final layout, care must be taken to adjust the size of the apertures of each of the color filters to achieve the desired white balance / color temperature while maximizing the brightness. If given a choice, the highest color temperature backlight should be specified as it allows the blue subpixel to be minimized, and the red & green to be maximized, to create the best uniform appearance and brightness when displaying black text on white backgrounds.

Conclusions and Implications

Subpixel rendering on the conventional RGB provides increased addressability, and therefore lower phase error, in the horizontal axis only. This improves Western fonts, especially Roman and Cyrillic, since they have higher spatial frequency components in the horizontal than in the vertical axis. (Historically, the Color Graphics Array, CGA, format took advantage of this by defining pixels that were taller than wide.) However, non-Western fonts, such as Kanji, have equally high spatial frequency components in each axis, and thus require increased addressability, and preferably higher MTF, in each axis.

The RGB stripe layout is non-rotationally symmetrical. Turning the display ninety degrees, from landscape to portrait mode, means that the increased addressability is in the wrong axis for Western fonts, lowering its utility for eBook and convertible monitor applications using Western fonts.

The *PenTile Matrix*™ layout is rotationally symmetrical with equal addressability and higher MTF in each axis, consistent with eBook, swing monitor, and non-Western font applications.

By optimizing the sub-pixel arrangement for sub-pixel rending, a novel display emerges that will set the standard, a standard that provides quad resolution images at a similar cost to that of conventional RGB stripe panels.

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